DDM – An Approach Towards Sustainable Production?

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Abstract

Direct Digital Manufacturing (DDM) is often regarded as the future of manufacturing. Since the future will be governed by questions of sustainability (e. g. availability of resources, emission prevention and fair production standards) DDM has to be analysed and optimised with respect to this. In this paper we will address sustainability aspects regarding two distinct development directions in DDM: the replacement of industrially established processes by additive manufacturing and the FabLab movement as an example of paradigm shift in consumer-producer-relationship.

Introduction

The use of resources in developed countries has to be reduced significantly during the next 40 years. Some frequently discussed goals are:

- Reduction of carbon dioxide emissions down to 1 tonne per year and capita in 2050 (today 10 t/yr·cap) [1]
- Reduction of average power consumption to 2000 W per capita (today 5000 W/cap) [2]
- Reduction of total material requirement to 6 tonne per year and capita (today 80 t/yr·cap) [3]

Reduction of energy, resource consumption and emissions by factors between 2.5 and 13 cannot be managed by increasing efficiency of already existing products and processes only. In the future an integrated and holistic approach is mandatory to rebuild the whole production system. Therefore a single-edge approach is not sufficient: Energy efficiency, recycling, renewable resources, lightweight-design, extended lifetime and the avoidance of overproduction have to be taken into account simultaneously.

DDM is often regarded as an important technology which will change the future production system, but will it do this in a sustainable manner? The well known advantages of a DDM technology, which might lead to sustainable production, are

- Production on demand, i.e. no excess production
- Tool and mould-free process
- No material loss (chips) during processing as in milling or turning
- Lightweight design by highly optimised structures
- Production of spare parts to increase longevity

There are many DDM-systems using layer-upon-layer deposition principles starting from different physical states (liquid, powder, melt) and various materials (plastics, metals, ceramics). In recent years there has been a trend to establish some of these additive techniques in industrial manufacturing with the objective to replace conventional foundry or milling technologies. Selective Laser Sintering (SLS) is one of the most promising candidates as it is able to generate durable, resilient parts, whose mechanical properties are comparable to injection moulded parts.

On the other hand DDM is the technological backbone of the FabLab movement [4]. FabLabs are open high-tech workshops where individuals have the opportunity to develop and produce tailored things which are not accessible by conventional industrial scale technologies. Furthermore, FabLabs are strongly connected to social web activities and therefore they are based on the idea of collaboration, decentralization, participation and democratisation [4, 5]. FabLabs and especially DDM, could therefore be part of a new mode of innovation, production and consumption.

Selective Laser Sintering in DDM

Most SLS prototypes and functional parts produced today are made of Polyamide 12 (PA12) or composites based on this polymer. Polyamide 12 is a semicrystalline and therefore strong and tough polymer with a good resistance against oils, fuels and light alkaline solutions. In Tab. 1 the mechanical properties of injection moulded PA12, PE and PP are compared with laser sintered PA12. Taking into account that during laser sintering neither shear action nor pressure occurs and that dogbones are typically sintered in an upright (weaker) orientation the mechanics of the laser sintered PA12 are quite good.

	Injection moulded			SLS
Property	PA12	PP	PE-HD	PA 12
Ultimate Tensile Strength [MPa]	35	32	30	39
Young's Modulus [MPa]	1600	1450	1000	1500
Elongtion at break [%]	7	70	12	12

Tab. 1: Mechanical properties of laser sintered PA12 [good] and injection moulded PA 12, PE-HD and PP

	SLS		manual	injection moulded		metal processing		
	PA12	CR-PA12	CRP*	PP GF30	PA12 GF50	Duralu-minium	Steel	High perf. steel
Density [g/cm^3]	1	1.1	1.5	1.1	1.43	2.7	7.9	7.9
Young's Modulus [N/mm^2]	1500	8928	140000	7000	13000	70000	200000	200000
Strength [N/mm^2]	43	84	1 500	100	167	400	500	1 800
Specif. Young's Moduls [Ncm^3/mm^2g]	1500	8138	93333	6250	9091	25900	25300	25300
Specif. Strength [Ncm^3/mm^2g]	43	76	1333	89	116	148	63	228

Tab. 2: Properties of different construction materials (*values in fibre direction)

The good mechanical properties are a result of the specific processing regime. Sintering is a highly transient process due to the high laser energy concentrated in a beam of very small diameter - several kW/cm^2 are achieved easily. But once the material has melted the polymer is held in a meta-stable state above crystallisation temperature for a long time (some hours to several days) and cooled down very slowly to prevent deformation and curling effects. Due to this the crystallinity of sintered polyamide is much higher than that of an injection moulded one. The slow cooling velocity causes large spherulites and thus high strength, high Young's modulus, high abrasive resistance and low moisture absorption capacity [6]. Goodrich [7] shows the better moisture and water resistance of laser sintered PA12 compared to injection moulded polyamide. His investigations of the long-term aging of polyamide laser sintering material show that laser sintered parts hold their strength at high temperatures better than injection moulded samples. Unexpectedly, the tensile strength of the laser sintered parts increased in the first weeks of storage under different conditions. Sintering parts by SLS takes a long time – but it seems that from a mechanical point of view this time is of value.

SLS for lightweight design

Theoretically, geometrically highly optimised, lightweight structures can be built by generative manufacturing. But the mechanical properties described above are poor with respect to the requirements in modern lightweight design. Even newer carbon short fibre reinforced PA12 sintermaterials [8] cannot compete to typical light weight materials (e.g. CRP). Mechanical properties of SLS parts currently do not exceed values of conventional glass fibre reinforced injection moulding grades based on PP or PA12.

Tab. 2 shows the material properties of lasersintered polyamide in pure (PA12) and carbon reinforced mode (CR-PA12) compared to other construction materials. Its Young's Modulus and strength are very low and are not compensated by its low density. Therefore, the specific material properties which are of great importance in light weight construction are worse compared to the construction materials shown: CRP shows a specific Young's modulus which is 62 (12) times higher and a strength which is 31 (17) times higher. Even ordinary steel shows a 17 (3) times better specific Young's modulus than laser sintered PA12 (CR-PA12).

Hence, it seems hardly possible to compensate such shortcomings by structural optimisation to reach lightweight design. Therefore, the development of new, optimised materials for SLS and DDM in general is inevitable. But the values for short fiber reinforced CR-PA12 sinter powders show that this will be a challenging objective.

Aging and recycling of sinter material

SLS powders are not modified by any anti-oxidants [9] as injection moulded qualities are. But by decreasing the moisture content of the PA12 laser sinter powders and by avoiding of oxygen during the SLS process by inertisation with nitrogen it is possible to reduce aging to achieve the good mechanical properties described above.

Nevertheless the long thermal impact during the building process causes an aging of the polymer which can be seen by Differential Scanning Calorimetry (DSC) and viscosity measurements of samples stored at 170 °C in an inert atmosphere [10]. After 16 hours of exposition the melting temperature increases from 185.7 °C to 190.4 °C while the crystallisation temperature increases from 145.8 to 148.1 °C; at the same time the enthalpy values decrease. The viscosity increases by a factor of five during a thermal treatment of 64 hours.

Therefore two aging mechanisms are assumed: chain-extension (cross-linking) and chain-degradation both caused by hydrolytic and thermal-oxidative processes. After longer times the effect of degradation of polymer chains becomes dominant.

The parallel effects of chain degradation and extension during aging do not significantly influence the mechanical properties of the part negatively. Taking into account the high temperatures and duration this result is surprisingly positive.

Nevertheless increasing melt viscosity reduces part quality and caking of powders by crosslinking hinders powder dosage in re-use. Therefore, to optimise the reproducibility of the process and the quality of the produced parts a percentage of 30 to 50 % of fresh powders is used today.

DDM Technologies are often regarded as wastefree. But during a typical SLS building job with PA12 material, only 5 % of the deployed powder material is in the final built part. Assuming a low refresh rate of 30%, this means that 25% of the material is lost or 5 times more material is wasted than it is in the product!

Other DDM processes might have much lower losses of processing materials (e.g. FDM). But often they do not show material properties suitable for long-life production parts or additional materials are needed to support the structures during manufacturing.

Energy demand in SLS

In SLS to avoid curling and to achieve dimensional stability the temperature of the powder cake has to be kept between crystallisation and melting temperature. Therefore the energy consumption of the whole process is dominated by the melting temperature of the polymer that will be used. Energy demand of SLS nowadays ranges between 40 to 400 MJ per 1 kg part weight [11]. The theoretical value for melting PA12 at 185 °C is around 0.4 MJ/kg [12]. Deviding these two quantities an energy efficiency between 0.1 and 1 % is achieved! Compared to injection moulding where efficiency reaches more than 60% [13] this is a poor value.

Table 3 shows that the chamber heaters and laser account for 55 % of the total energy consumption. Nevertheless an amount of 45 % for stepper motors and roller drives show that processing time is long and the equipment features are not working very efficiently.

Part of the SLS machine	Percentage of total energy consumption
Chamber heaters	35 %
Stepper motors for piston control	25 %
Laser	20 %
Roller drives	20 %

Tab. 3: Energetic view on the SLS-process [15]

Making polymers like PEEK (melting temperature 335 °C) available for SLS [14] will lead to even more energetically inefficient processing.

Ecological footprint

It has been shown that allthough SLS is a mould and tool-free process the process is extremely inefficient with regard to the energy consumption. Furthermore the process is not waste-free due to the aging of the powder during the building process, which requires a fresh-rate much higher than the material used for the part.

Injection moulding is the dominating technology to produce parts of thermoplastics and the SLS technology has to compete with it, when it will enter real manufacturing. In principle both processes start with similar raw polymers while injection moulding requires granulate material and SLS powder material with a size below 100 microns. PA12, the mostly used material for SLS, can be produced in powder form directly. Most other materials would have to be micronised in an extra step. Due to the viscoelastic material properties comminution of plastics is very energy consuming, ranging between 500 to 1.000 kWh/tonne [16].

To compare different contributions to the ecological impact of one part, these have to be measured by a common weight. One concept is the Material Input per Service Unit (MIPS) developed and published by the Wuppertal Institute [17]. Here all contributions are measured in “use of abiotic mass equivalents”. Other possibilities would be the calculation of the carbon footprint, cumulative energy demand or others. Each method puts different weight on different aspects, so they might lead to slightly varying results, but the trend should be the same.

Table 4 shows a MIPS calculation for injection moulding of Polypropylene and SLS (some data are taken from Polyamide 6.6 because no data are available for PA12). For injection moulding an overall number has already been published while for SLS the steps are shown separately.

	Injection Moulding (PP)		SLS (PA12)		
Contribution	Amount	Abiotic Mat.	Amount	Abiotic factor	Abiotic Mat.
Raw material	1 kg	2.09	1 kg (PA 6,6)	5.5 kg/kg	5.5
Loss material			5 kg	5.5 kg/kg	27.5
Grinding			800 kWh/ton	3.15 kg/kWh	15.1
Liq. Nitrogen			2 kg/kg	0.8kg/kg	9.6
Processing			60 kWh/ kg	3.15 kg/kWh	189.0
Inj. Moulding (overall)	1kg	2.15			
Sum		**4.09**			**246.7**

Tab 4: MIPS calculation for injection moulding and SLS

The comparison is clearly dominated by the high electric energy consumption during the slow building speed in the SLS process. This is calculated with the value for electricity in Germany, in other countries with a higher rate of renewable energies in the production of electricity (e.g. Norway) this might look differently. But nevertheless the injection moulding process is far more efficient by a factor of 60.

DDM would offer the possibility to produce the products close to the customer. Hence, the need for transportation would be reduced. But despite the controversial discussion about too much transport, transportation is not relevant here: Tab 5 shows the use of abiotic material to transport the mass of 1kg over a distance of 1000 km.

Contribution	Abiotic factor	Abiotic Mat.
Transport rail	0.08 kg /ton/km	0.08
Transport truck	0.22 kg/ton/km	0.22

Tab 5: Use of abiotic material to transport 1 kg of material for 1000 km

Hence, future developments should focus on an increase in powder re-use, a better insulation of the powder chamber and a considerable reduction of processing time as well as on new low temperature polymers. Regarding the latter a promising candidate might be newly developed thermoplastic polyurethane (TPU) sinter powder [18].

The role of DDM in the transformation of the production and innovation system

The desire to offer custom-made mass products which becomes possible by using DDM is not new. »Production on demand«, »co-production«, »agile manufacturing«, »modern manufacturing« or »mass customisation« are only some of the keywords referring to the same thesis: Mass production has passed its peak and production processes have to be more flexible, serving the individual consumer perfectly. Taking this into consideration new business models where came up at the end of the twenthies century. »Just-in-time« production and deliveries save storage and guarantee a flexible reaction to demand fluctuations [19]. Nowadays, with the help of new communication and manufacturing technologies, new dimensions of flexibility can be reached. Sustainable Development until now is not the initial thought behind those concepts - companies simply wanted to increase productivity and open up new market potentials.

In contrast to the traditional factory chain concept (sequentially added production steps), the concept of interactive co-production is an effective way of designing products for the customer [20]. Hastings research in the early 90s on the organisation of dynamic project teams (abolishing rigid hierarchies, where communication patterns are narrowly defined, in order to build up role-orientated teams instead, which can react fast to new market demands) [21], is valuable for bursting boundaries today: Breaking down the wall between company (inside) and the customer (outside). Separations are fading more and more, when looking e. g. at the renewable energy market (solar panels on private roofs or CO_2-neutral islands [22]).

The digital age allows quick data exchanges and provides convenient 3D-construction software for plenty of people, while additive manufacturing like SLS allows a quick, tool-less, plug&play production of highly customised design parts. The symbiosis of those technologies has already led to innovative business models in the dental industry [23]: The scanned data of a tooth is sent to a company, which sinters the custom made replacement quickly. The next generation of business models will combine additive manufacturing and open-innovation concepts to gain even more insights and flexibility regarding customer interests.

Besides the development described above which is still governed by industrial interests and take place top-down from industry to customer, there are also some strong and viral bottom-up movements based on the idea of autonomous, local and personalised innovation and fabrication as well as collaboration and democratisation (instead of competition) as a driver of progress. FabLabs, personal fabricators and self-repair-communities are some shapes of this movement.

The idea of FabLabs started in 2002 at the MIT. Small groups of people engage in open and collaborative high-tech workshops to individualise design, products and new manufacturing processes. The equipment of a FabLab typically consists of 3D-printer, laser cutter and milling machine. Nowadays more than 100 FabLabs worldwide can be counted [24]. The first German FabLab started as late as 2009 at the RWTH Aachen. Surprisingly, this development is not restricted to developed countries only, but also takes place in Africa and Asia - even Afghanistan possesses a FabLab. Therefore the idea of FabLabs affects one of the main ideas of sustainable development: balancing human welfare, fairness and participation on a global scale.

DDM and especially 3D-printers based on Fused Deposition Moulding (FDM) are the technological backbone of the FabLab movement. In 2008 the first low price 3D-printer named RepRap was presented. The RepRap is sold as a construction kit: Most of the parts can be 3D-printed (one of the main ideas of fabbing is self-replication of production machines). The other parts are easily available in each construction store. The RepRap (GB) was followed by the MakerBot (US) in 2009, the Ultimaking (NL) and the ShaperCube (D) in 2011. Three further 3D-printers, Fabbster (D), iRapid (D) and MakiBot (Cn) are announced for 2012. Prices decreased at the same time from about US$2000 to US$300.

No matter weather top-down industrial mass customisation or the bottom-up democratization of production will be the dominant driver in future, DDM-technologies will dispread with high speed through industry and society. Nevertheless, individualised small-scale production lacks in efficiency. In a broad study on energy efficiency of various manufacturing technologies Allwood et al. showed that at process rates below 10 kg/h energy efficiency decreases by magnitudes. At 0.1 kg/h efficiency decreases by a factor of 1000 [25]. Values for injection moulding (high process rates) and laser sintering and melting (low process rates) prove this findings. This shows clearly that if FabLabs and especially personal fabricators are supposed to positively contribute to sustainable development they have to overcome today's constraints of low efficiency in small-scale and early product life cycle stages. Taking into consideration the fast spreading of 3D-printers during the last four years this is of great importance.

A production scenario based on personalised additive manufacturing sometimes is assumed to reduce transport. But this will only be true when locally available materials are used for the production of things and the personal fabricator itself. But nowadays construction kits and materials are sold worldwide.

Materials for personal fabrication available today are mainly based on fossil acryonitrile butadiene styrene (ABS). But with polylactic acid (PLA) a promising biobased alternative has already entered the market. The quality of the surface of the parts produced may achieve 30 µm which is poor compared to injection moulding. Thinking in terms of consumer products one of the most interesting properties of polymers is their ability to mould all kinds of surface structures such as polished surfaces or leather-like surfaces. Therefore either the acceptance of rough surfaces or technologies to finish them have to be developed. Otherwise DDM-products will be placed in technical surroundings (e. g. under the hood) but they do not interact directly with the consumer.

With respect to recycling Gutowski and Dahmus showed that there is an apparent boundary which defines if recycling does make sense or not [26]. Low dispersion of materials and high overall material values of the product favour recycling. Today the recycling of plastic bottles and steel cans makes sense even at low overall material values of US$50 million because dispersion is very low. In contrast computer recycling despite an overall material value of about 1 billion dollars does not make sense since the degree of material dispersion is too high. Therefore the utilisation of only few materials and the ease of disassembling should be an important technical guideline for future developments of the personal fabricators and the things produced with it. Unfortunately the current problems in personal fabrication addressed by the community are dominated by lack in technical functionality only (speed, resolution and the limited availability of different colours, materials and 3D-models). Aspects of sustainability (e. g. resource use) are not mentioned except for some concerns about volatile emissions assumed to have toxic effects caused by thermal degradation of the printing material [27].

Significant sustainability effects are expected in terms of product longevity. As the consumer is responsible for the design of the sintered products and components, he will probably not throw them away thoughtlessly. The same effects are well known, when it comes to self-manufactured or home-made items. This deeper psychological connection between customer and consumer good leads to a more careful handling. Furthermore repairing complex products and producing spare parts will become easier. Life cycles of complex products could extend decisively as many items are thrown away today because no spare parts exist or repairing them is too expensive.

Conclusions

Over 1.7 billion people worldwide belong to the »consuming class« by now [28]. It is expected that in 2050 about 4 billion people will share the life style of the developed countries. Nevertheless, regarding resources and emissions this will simply not be possible. In order to reduce the ecological footprint of consumption decisively, the whole system of producing and consuming thus needs to be innovated.

Based on a foresight-process report of 2009, the research field »ProductionConsumption2.0« became an important issue in the funding activities of the German Federal Ministry of Education and Research. The change of material flow patterns, and especially the »paradigm shift to personalized production, e.g. in generative processes« is one important driver for the new research field [29].

Unfortunately different players and stakeholders in this field until now neither reflect the needs of sustainable development nor include it in their action plans. The dominant SLS-technology lacks in energy efficiency and recyclability, light weight potentials are limited because suitable materials are not available. Within more than 100 FabLabs we did not find one with a strong focus in sustainability.

Nevertheless, participation, collaboration and self-fabrication increase the responsibility of everybody which should be an excellent base for a sustainable consumer-producer-relationship. It revives the idea of the traditional locally established handicraft business without rejecting the process of globalisation and the use of high tech methods. It's high time for the first sustainable FabLab!

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